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Using the Circulating Beam in the Fermilab Antiproton Accumulator for Experiments*

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ABSTRACT

The Fermilab Accumulator is a storage ring optimized for stacking and stochastic cooling 8 GeV antiprotons for the Tevatron collider. Minor modifications have been made to provide for beam in the energy range 8.0–2.9 GeV of luminosity $\sim 10^{31}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ with a hydrogen jet internal target. Experience to date consists of machine studies and detector engineering run with protons.

1. Introduction

The Fermilab Accumulator is a specialized storage ring designed as a dedicated facility for stacking and stochastically cooling 8 GeV† antiprotons for Tevatron collider operation. However, its potential as a source of $\bar{\mathrm{p}}$'s for low energy particle physics[1,2] and nuclear physics[3] was apparent even before it came into operation in 1985. Fixed target operation of the Tevatron not only frees the Accumulator of its principal function but also leaves the 150 GeV main ring injector available about half of the time for $\bar{\mathrm{p}}$ production cycles. Although the accumulation rate is reduced because of the limited availability of the main ring, the Antiproton Source including the Accumulator is otherwise uncompromised by the fixed target program. The first approved experiment[4] is a study of charmonium states formed at threshold in $\bar{\mathrm{p}}\mathrm{p}$ collisions using a hydrogen jet in the circulating beam, a second generation of the R704 ISR experiment.[5] In addition to substantial physics interest this experiment has the advantage of requiring only modest changes to the Accumulator and its enclosure. In this talk the emphasis is on the accelerator aspects of the required modifications, beam studies, and engineering run for a Phase I version of the detector. The studies were conducted with protons and reversed magnet polarity; a single booster batch of protons easily provides an appropriate beam current which would take several hours to accumulate in antiprotons. Most features of the tests are independent of the beam particle.

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† **Throughout this talk proton kinetic energy in GeV is used.**

2. Accumulator Operating Mode

To accumulate the number of p̄'s needed for the experiment the Antiproton Source operates exactly as it would for the collider[6] except that the main ring can not execute production cycles during injection into the Tevatron and at certain times during the Tevatron cycle when the two machines interact too much through stray magnetic field in the common tunnel or through the power mains. To decelerate the beam to the experimental energy requires some modifications of the Accumulator and operation in modes unforseen in the design. The beam is moved from the orbit of the accumulated core near the edge of the vacuum chamber to the central orbit for deceleration. The move is required because the magnets, designed for maximum good field region at 8 GeV, are significantly into saturation and therefore have narrower good field region at lower energies. Also, the beam width increases during deceleration because of the natural increase of transverse emittance proportional to p^{-1}, because of the increased momentum spread arising from bunching, and because of imperfect control of machine parameters.

There are about 90 devices including bend bus, three quadrupole busses, three quad bus shunts, four sextupole busses, two skew quad busses, and more the 60 trim elements which need to be ramped synchronously and smoothly as the energy is changed. The various busses have a variety of natural time constants as well as differing levels of core saturation. Because the natural time constant on the bend bus is $\sim$ 200 ms, deceleration is necessarily a leisurely process. Therefore, although a considerable number of devices must be ramped, the setting rates can be in the range of Hz or tens of Hz. On the basis of the bend bus slew rate one could expect to decelerate at a rate $\gtrsim$ 100 MeV/s.

In fixed energy operation the power supplies are controlled by DAC's connected to a serial CAMAC system. The rate and timing precision with which the DAC's can be set by the control computer network is completely inadequate for deceleration. Because the number of devices is not too large and the Accumulator is compact, it was possible develop an adequate source for all of the ramps primarily in software.[7] The crate controllers in the serial system are a dual-ported Fermilab design with hardware arbitration intended for a local console. An additional PDP 11/44 front end was installed on the control network to communicate only with the devices to be ramped through these unused crate controller ports. The new computer looks to the control network like a typical front end, but its function is limited to providing settings for 10 devices at 60 Hz and 80 devices at 1 Hz. New curves are calculated and sent to the auxiliary front end from a standard control console in the standard manner.

The change in frequency during deceleration moves the rf excitation away from the resonant frequency of the cavities. The Accumulator cavities have been heavily de-queued to preserve longitudinal stability of beam with low momentum spread, so fine tuning of the cavities in precise synchronism with the deceleration cycle is not needed. However, remotely adjustable mechanical tuners were added to the stacking system cavities to permit setting them to an appropriate resonance for each of several successive decelerations should it be necessary or helpful.

The rf excitation itself, however, must be rigorously synchronized to the change in magnetic field to avoid beam loss or unnecessary increase in momentum spread.

The original VCO rf source has therefore been replaced with a wide-range, low-phase-noise, digital synthesizer. The synthesizer frequency must be set every keV or so of deceleration to avoid shaking the beam. Therefore, the synthesizer is run by a Motorola 68000 microprocessor which interpolates between the points provided at 60 Hz by the auxiliary front end at up to a 20 kHz rate. This setting rate is probably the limiting factor on deceleration rate. The microprocessor controller also filters the frequency curve it receives to match it to the time constant of the bend bus.

It is crucial to the physics application that beam cooling be available at the lower energies to restore the beam brightness after the deceleration and to maintain the luminosity lifetime against the effect of scattering in the target. The variable energy mode places two new requirements on the core cooling systems. Most fundamental is the need to compensate for the change in beam circulation frequency by adjustable delays between the pickups and kickers. New computer setable delays allow the cooling to be set up anywhere in the energy range. To maintain a cooled beam in the center of the aperture the core systems are switched to a new set of kickers and pickups installed on the central orbit. The effectiveness of the cooling system at a particular energy depends on how close it is to the synchrotron transition energy of the magnet lattice. The transition γ itself, however, can be varied up to one unit by changing quadrupole currents without loss of stored beam, permitting adequate cooling throughout the 2.9–8 GeV range.

There were about two months of beam time available over eight months of the 1987 fixed target run. The highest priority has been to obtain low beam loss in the deceleration process. Most of the beam time was devoted to the empirical adjustment of magnet current and rf system programs and to making accelerator measurements related to beam loss and stability. All such information was new because the Accumulator had previously been operated only at 8 GeV.

Typically 1–30 mA of 8 GeV protons were cooled on the central orbit to $\Delta p/p = 0.06\%$ (FW 10% max) or $\sim$ 8 eVs longitudinal emittance; 1 mA is 10^{10} protons. These were adiabatically captured and decelerated by the 53 MHz stacking rf system providing 15 eVs of bucket area. The observed loss of a few percent after about 100 MeV of deceleration results from uncaptured beam reaching the vacuum chamber wall. Because $\Delta p/p \sim 0.04\%$ is typical of the cooled $\bar{p}$ core, these losses will be somewhat less; a further slight improvement may be obtained from smoother amplitude control and reduced rf noise during the capture.

A priori calculation of programs from magnet data was inadequate to keep any beam for more than a few hundred MeV of deceleration, so the ramp curves were built up in a tedious cycle of decelerations of about 40 MeV followed by correction of tunes, closed orbit, chromaticity, coupling, and so on. Because the corrections are strongly interdependent the entire sequence of decelerations had to be repeated many times, a process which was practicable only because the deceleration and measurement sequences were largely reduced to control programs,[7] leaving people free to focus on interpretation. The calculated corrections to the curves at each step were smoothly propagated back to the previous point corrected and forward to all succeeding points in the form of the existing curve.

Deceleration efficiency to 4.2 GeV, just above transition, became routinely about 85%. The principal cause of loss appears to be escape from the decelerating bucket driven by several 60 Hz harmonics. Although the strongest sidebands are at least 45 dB below the carrier, any part of the longitudinal distribution with synchrotron frequency at harmonics in the range 120–720 Hz was observed to be significantly excited. The resulting loss appears as a more or less steady diffusion from the bucket over some 200 s of deceleration. The most efficient deceleration has been at 20 MeV/s; why the optimum should be this low has not been clearly established.

During deceleration the transition energy is smoothly ramped from its nominal value of 4.2 GeV (kinetic) to 3.9 GeV. At 4.2 GeV the beam is debunched and quadrupole currents are changed over about 2 s to move the transition energy up to 4.8 GeV. This so-called γ_t jump has an efficiency of about 98% for 8 mA of beam which drops to about 85% for 12 mA. That the momentum spread of an 8 mA beam blows up from 0.2% to 1% during the γ_t jump demonstrates that, not surprisingly, longitudinal stability is the crucial consideration in this process. The threshold for self-trapping instability is proportional to $\gamma_t^{-2} - \gamma^{-2}$. This is a fundamental limitation which will always limit intensity at some level regardless of improved hardware or technique. It may be possible to speed up the jump enough to reduce the blowup.

After the transition crossing it is critical to cool the beam longitudinally for recapture. The beam has been cooled to < 6 eVs for capture into 56 eVs of bucket area; the extra bucket area is unfortunately necessary because so far there has been beam blow up as soon as the longitudinal cooling is turned off in preparation for capture. The recapture is about 97% efficient, but the stacking system rapidly runs out of bucket area as deceleration proceeds away from transition. The difficulty is reduced somewhat by ramping the transition energy back to its design value. There are several further measures which can be expected to provide satisfactory deceleration efficiency below transition. More bucket area may be provided by using an existing 1.2 MHz rf system, the blowup at transition may be better controlled, and additional cooling may be carried out further from transition where there is no stability problem. Beam phase feedback to the rf and transverse dampers may both reduce deceleration losses in general; provisions exist for both, but neither has been exploited effectively yet. The best overall deceleration to 2.9 GeV has been 60% efficient with an initial 8 mA; efficiency decreases with higher beam current primarily because of problems associated with transition crossing.

3. Status of the Charmonium Experiment

A vertical beam scan has shown a jet of about 5 mm FWHM with the area density of $10^{14}\,\mathrm{cm}^{-2}$ required for the experiment. To reach the proposed luminosity of $10^{31}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ it will be necessary to decelerate 15 mA of beam efficiently. The jet density can be raised easily, but the deterioration in beam lifetime precludes much gain in this way. Beam lifetime in the absence of the jet target has been 400 h at 8 GeV and 100 h at 4 GeV in agreement with p^{-2} scaling expected from beam-gas multiple scattering. With the jet running continuously the lifetime drops by a factor of two.

The installation for the experiment has involved providing a ground level counting room addition to an Antiproton Source service building, extending the tunnel inward to provide a roll-out and assembly area for the detector, and excavating a detector pit about 14 ft (l) $\times$ 8 ft (w) $\times$ 3 ft (d) at the center of the AP-50 zero-dispersion straight section, which is unencumbered by stochastic cooling hardware. The experimental equipment tested during the engineering run includes a forward calorimeter, luminosity monitor/recoil proton telescope, sixteen cell threshold Čerenkov counter, and "straw tube" drift tube hodoscope. The major item in the detector is a 1280 block lead glass calorimeter with vertex pointing geometry which will be tested in the 1989 run; physics data taking will also begin during this run.

There is still much room for improvement in the performance of the Accumulator as a variable energy storage ring and major work lies ahead on the detector. However, in both respects the 1987 engineering run demonstrated that the experimental proposal is realistic and that all or nearly all of the detector is on schedule for preliminary data taking in 1989.

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